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The Implications of the Iceland Deep Drilling Project for Reducing Greenhouse Gas Emissions Worldwide

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ABSTRACT

To mitigate climate change, it is imperative to reduce emissions of greenhouse gases (GHG). Renewable resources should play a greater role in that endeavor by reducing use of hydrocarbons for electrical generation. Unlike intermittent resources like solar and wind, geothermal energy provides baseload power, that can be cost competitive with those intermittent resources. However geothermal power has higher capital costs and longer lead times to develop and furthermore generation using geothermal steam is not entirely GHG free, although emissions are only about a third of those from natural gas fired turbines. However, the GHG emissions produced by transportation far exceed those from electrical generation in California, USA, for example, as in all industrialized societies worldwide. This requires greater use of zero emission vehicles, powered by electricity or by hydrogen.

Iceland is leading the way with the Iceland Deep Drilling Project (IDDP) which is exploring for and developing supercritical geothermal resources, The success of the well IDDP-2, a 4.5 km deep geothermal well at Reykjanes, in Iceland, that penetrated supercritical conditions, (bottom hole temperature of ~600°C) suggests new possibilities for both improving geothermal economics *and* reducing GHG emissions. Because of the higher enthalpy and more favorable flow characteristics of supercritical water, a supercritical geothermal well should produce an order of magnitude more power than is available from a conventional geothermal well. Producing much higher temperature working fluids creates other possibilities to improve geothermal economics by making downstream processes more efficient. Flexible downstream use of the high-temperature fluids produced, principally by making hydrogen, would make the resource even more valuable. This could be done by selling electricity when demand is high, and at times of lower demand using electricity to produce hydrogen by electrolysis of hot water. This is especially advantageous in markets like California where there is a risk of overgeneration due to large amounts of solar generation. Electrolysis is more efficient at high temperatures, but electrolytic cells require clean water, so heat exchangers and/or desalination would be necessary. Similarly, when the chemistry of geothermal brine is suitable, salable products such as lithium, base metals, and other mineral products could be extracted from the brines. Another project in Iceland is sequestering CO_2 by injecting it into hot rocks in geothermal reservoirs, where it is fixed by forming carbonate minerals

Development of supercritical and superhot geothermal generation would reduce emission of GHG's by (1) replacing the use of the hydrocarbon fuels to produce electricity, (2) using electrolysis to produce hydrogen, as a transportation fuel or as a form of energy storage, (3) sequestration of CO_2 in geothermal reservoirs, (4) producing lithium from geothermal brine (reducing the price of batteries used in zero emission vehicles), and (5) extracting metals like zinc, silver, lead, manganese, from geothermal brine (without the GHG produced by smelting). These concepts could be used worldwide wherever suitable high temperature geothermal systems exist. Successful adoption of these technologies would contribute to the growing worldwide demand for alternative energy and lead to significant reductions in GHG emissions.

1. INTRODUCTION

This paper discusses the implications for the future development of the geothermal industry by using supercritical or superhot resources for production of hydrogen, metals, especially lithium, desalinated water, and various direct uses, and the contribution that this would make to reducing emissions of Green House Gases. We are applying the term "superhot" for fluids that are above supercritical temperature but below supercritical pressure. The theme of this paper is that adoption of this approach would also reduce emissions of GHG, worldwide and specifically examines its potential to reduce GHG emissions in the case of California, USA, as an example.

2. RENEWABLE POWER PRODUCTION IN CALIFORNIA

Unlike the intermittent generation from solar and wind power, geothermal generation has the advantage of providing baseload power. However, in certain circumstances this is not an advantage. For example, in California, USA, the rapid development of solar power is causing problems in balancing the grid. In the early evening, when the sun goes down, the demand for electricity remains high (Figure 1). In this environment any new sources of electrical generation should be flexible with respect to time of day, responding to the hourly changes in the ratio of supply to demand.

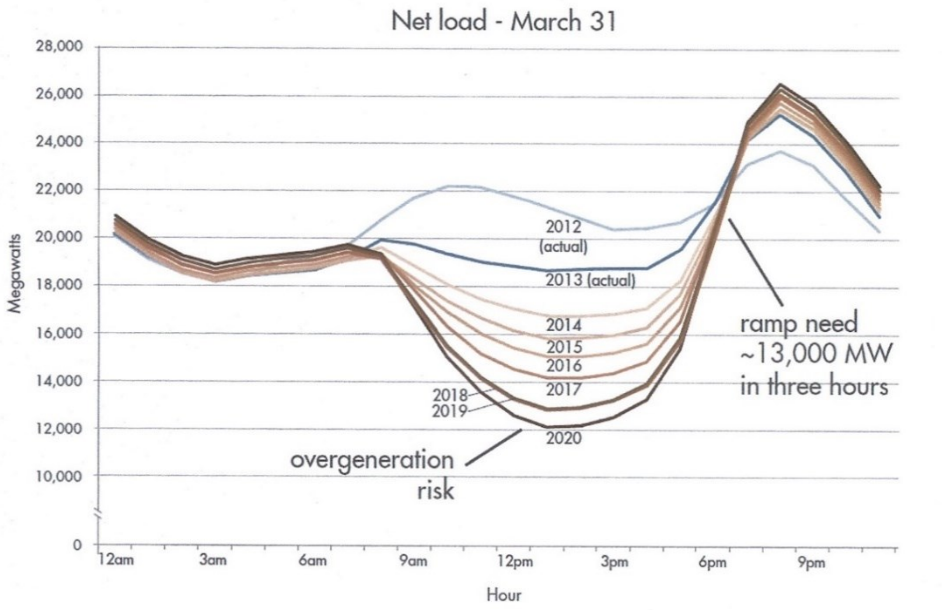

Figure 1: Projected daily electricity demand on a typical spring day in California. There is a risk of overgeneration in the middle of the day and early afternoon, followed by a steep ramp where an additional 13 GWe is needed (California Energy Commission, Annual Report, 2017).

Recent cost comparisons between various types of renewable power generation indicate that, even without subsidies for renewable energy, in the appropriate circumstances geothermal electric power can be cost competitive. For example, the unsubsidized cost of community PV generation is estimated to be between $76/MWh and $150/MWh, while geothermal generation is estimated to cost between $77/MWh to $117/MWh (Lazard, 2017). However, development of geothermal resources has the disadvantage of requiring large front-end investments before producing electric power. Lazard (2017) estimated that the capital cost per installed megawatt for geothermal power lie in the range of $4,000 to $6,000/kWh whereas the capital costs for installing community solar PV are only $1,550/kWh to $3,100/kWh. Furthermore, solar PV can be installed rapidly, whereas a "greenfield" geothermal development can take 8 to 10 years to begin operation. Obviously, reducing costs and improving the reliability of exploration and drilling would directly address this problem. However, an international consortium, the Iceland Deep Drilling Project (IDDP), is taking a different approach, that is to produce supercritical geothermal resources to increase the power output per well. Currently interest in developing supercritical geothermal resources is increasing worldwide (Reinsch, et al., 2017).

3. SUPERCRITICAL GEOTHERMAL RESOURCES AND THE ICELAND DEEP DRILLING PROJECT (IDDP)

The IDDP is a long-term project by a consortium of Icelandic energy companies aimed at drilling deep enough to reach the supercritical conditions believed to exist beneath existing high-temperature geothermal fields in Iceland (Friðleifsson, Elders, and Albertsson, 2014). The critical point for pure water occurs at 374°C and 22.1 MPa, but it is higher for solutions that contain dissolved salts (Figure 2). The critical point is higher for solutions that contain dissolved salts. For example, the critical point for seawater is 407°C and 29.8 MPa (Bischoff and Rosenbauer, 1988).

Not only do such fluids have higher enthalpy than conventional geothermal reservoir fluids, but they also exhibit extremely high rates of mass transport due to the greatly enhanced ratios of buoyancy forces to viscous forces in the supercritical state (Fournier, 1999; Friðleifsson, Elders, and Albertsson, 2014). Elders et al., 2018 and Shnell et al., 2018 have discussed the relevant newer technologies that would be required to utilize these concepts. Modeling indicates that a well penetrating a supercritical geothermal reservoir could produce an order of magnitude more usable energy than that produced by a conventional high-temperature (~300°C) geothermal well 2 to 3 km deep. Thus, fewer wells are necessary for a given power output resulting in both lower costs and smaller environmental footprints. The first attempt to drill into a supercritical reservoir was made in 2009 in the Krafla caldera, in NE Iceland. However, the well (IDDP-1) did not reach supercritical fluid pressures because drilling had to be suspended when 900°C rhyolite magma flowed into the well at only 2,100 m depth (Elders et al., 2011**)**. When the well was tested, it produced superheated steam at 452°C at a flow rate and pressure sufficient to generate about 35 MWe. While flowing, this was the world's hottest production well, but after two years of flow testing repair of the surface installations was necessary, and the well had to be quenched due to failure of the master valves leading to premature abandonment of the well. The IDDP-1 well is described in 14 papers in a special issue of Geothermics, 2014, volume 49, (http://iddp.is/2014/01/15/geothermics-special-issue-on-iddp-january-2014/).

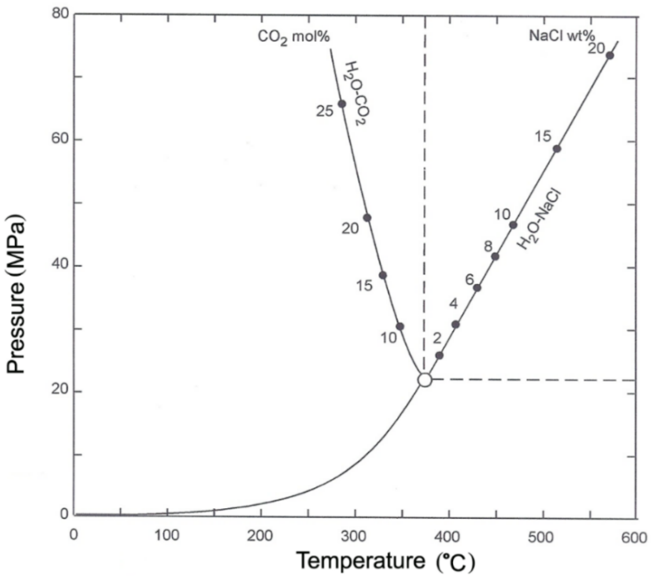

Figure 2. The boiling point curve and critical point curves for water. The critical point for pure water is indicated by the open circle at 374°C and 22.1 MPa. As shown by the relevant critical point curves for H_2O-NaCl and H_2O-CO_2, dissolved salt increases the temperature and pressure of the critical point whereas dissolved gas reduces the temperature and elevates the pressure of the critical point (Hashida et al., 2001).

IDDP-2, the second well in the series, was drilled to a vertical depth of 4.5 km in the Reykjanes high-temperature geothermal field in SW Iceland, on the landward extension of the Mid-Atlantic Ridge (Friðleifsson et al., 2018; Friðleifsson et al., 2020). The Reykjanes field is unique among Icelandic geothermal systems in being recharged by seawater. In January 2017, following only six days of heating, a temperature of 426°C at 34.0 MPa pressure was logged, confirming that supercritical conditions exist at depth. Inflection points in the temperature log occurred at ~3,400 m due to cooling at a major loss of circulation zone and at smaller loss zones at ~4,375 m and ~4,500 m. Whatever the fluid composition at 4.5 km depth, it is hard to argue that the measured temperatures and pressures are not supercritical. A long-term program of injecting cold water at 50 l/s was then begun to enhance the permeability of these deeper loss zones. A second series of temperature/pressure logs run from May 23-29, 2017 indicated that the permeability of the deepest loss zone had increased and yielded an estimated bottom hole temperature of 540^{o}C (Tulinius, 2020). Unfortunately, a constriction subsequently developed in the production casing at a depth of ~2.4 km that now prevents deployment of logging tools deeper.

Additional information on the downhole conditions of the IDDP-2 comes from the drill cores obtained. These sampled a series of dolerites (basalts) with chilled margins that are interpreted to come from a sheeted dike complex (Zierenberg et al., 2020; Friðleifsson et al., 2018).). Alteration mineral assemblages indicate a complex history of response to dike emplacement and hydrothermal alteration. Deeper than 3,825 m, the rocks are pervasively altered to amphibolite facies mineral assemblages that require a minimum of 400°C to form. As these dolerites lack microscopic porosity, the textures and minerals observed are consistent with alteration by high-temperature, very low viscosity, supercritical fluids. Various mineral geothermometers using partitioning of elements between coexisting mineral pairs indicate that near the bottom of the well, hydrothermal mineral alteration occurred at ~ 600^o C (Zierenberg et al., 2020). These alteration minerals in the deepest cores also indicate that this hydrothermal alteration involved seawater-derived fluids at supercritical conditions. Fluid inclusions are sparse and containing only vapor, or vapor plus daughter crystals. Careful study of these fluid inclusions confirms that alteration near the bottom of the well involved a ~600^{o}C, CO_2 -rich vapor and a concentrated Fe-K chloride brine (Bali, et al., 2020).

The more than year-long experiment of injecting cold water to stimulate the deep permeable zones in the IDDP-2 ended in August 2018, and the well began to heat up, concurrent with design and construction of the surface installations necessary for a long-term flow test, planned to begin in the autumn of 2019. Whatever the outcome of these planned flow tests, it is evident that the IDDP-2 has achieved its primary objectives of demonstrating, for the first time anywhere, that it is possible to drill into supercritical conditions and that permeability exists even in an environment approaching the transition from brittle to ductile behavior. The latest flow test results will be reported at the WGC-2020 meeting.

4. IMPLICATIONS FOR THE ENERGY MARKET IN ICELAND AND BEYOND

Supercritical conditions are not restricted to Iceland, but should occur deep in any young, volcanic-hosted geothermal system. Recent numerical simulations of magma-heated, saline, hydrothermal systems indicate that phase separation is the first-order control on the dynamics and efficiency of heat and mass transfer near intrusions (Scott et al., 2017). Above deep intrusions emplaced at >4 km depth, where fluid pressure is >30 MPa, phase separation occurs by condensation of hypersaline brine from a saline intermediate-density fluid. The fraction of brine remains small, and advective and vapor-dominated mass and heat fluxes are therefore maximized for exploitation of supercritical geothermal resources.

The potential advantages of the approach of accessing hotter and deeper supercritical and superhot geothermal resources include: (1) Improvement in the ratio of drilling costs to power output per well. Although deeper wells would be more expensive, this would be offset by much higher power output per well. (2) Improvement in the power output of existing geothermal fields without increasing their environmental footprints. (3) Improvement in the lifetime of existing geothermal fields by increasing the size of the producible resource by extending production downward. (4) Accessing deeper, hotter, environments for fluid injection. (5) Improvement in the economics of geothermal power production. Higher-enthalpy aqueous working fluids in a turbine have a higher heat-to-power efficiency and therefore should potentially yield more favorable economics.

5. COMBINED USE OF SUPERCRITICAL AND SUPERHOT GEOTHERMAL ENERGY

The marketability of new electrical capacity from more efficient supercritical (or superhot) geothermal resources depends upon both the local geology and the prevailing economics of electricity production and distribution. However, one thing they have in common is that pricing needs to be competitive. The unique feature of geothermal resources compared to other kinds of alternative energy is that geothermal wells produce combinations of heat, flashed steam, and hot brine. In this regard, the very high enthalpy of supercritical and superhot systems creates new opportunities to add value by (1) allowing flexibility in sales of electricity depending on time of day, and (2) more importantly adding revenue from downstream use of the hot fluids by, for example, making hydrogen, extracting dissolved metals and minerals, desalinating water, and finally direct use of the spent fluids. Such plants could sell electricity to the grid when demand is high and when demand is lower could use all or part of the electricity on site to make salable products.

5.1 Electrolysis and Desalination

At appropriate times of day, all or part of the electricity produced can be used for electrolysis to make hydrogen and oxygen from clean water. Today hydrogen is mainly used in industrial chemical and refining processes, in metallurgy, glass production and electronics, but it should have an even greater future as a transportation fuel. Currently, production by electrolysis of water is only a minor source of hydrogen as the dominant source of commercial hydrogen production uses industrial steam to reform natural gas. The availability of supercritical water would improve the economics of electrolysis relative to reforming natural gas. This could also be helped by carbon credits as reforming methane releases CO_2, whereas hydrogen fuel releases only water. But the main point is that, at supercritical conditions, electrolysis is much more efficient, and so the electricity needed is much less. Similarly, the use of very high enthalpy geothermal fluids in heat exchangers should make desalination more cost effective. New technical developments in electrolysis and desalination that promise to improve the economics even more have been described by Shnell et al. (2018).

5.2 Mineral and Metal Extraction

An additional source of revenue from supercritical and superheated brines would be extraction and refinement of metals and salable minerals from supercritical and superhot geothermal fluids. Many geothermal brines contain high concentrations of such potential products. Unusually high concentrations of metals occur in the brines of the Salton Sea Geothermal Field (SSGF) in southern California, which, among currently producing geothermal systems, has the most concentrated brines (up to 25 weight % TDS). The SSGF currently has an installed generating capacity of ~400 MWe, but the latest published estimate of its geothermal reserves, to 3 km depth, indicated that it could generate 2,950 MWe for 30 years (Kaspereit et al., 2016). Most of this large geothermal resource is undeveloped, largely because of the difficulties in getting power purchase agreements, due to competition from solar power. The undeveloped northern part of the SSGF is probably the largest known undeveloped resource in the world. The resource estimate by Kaspereit et al (2016) was based on production from depths of less than 2 km, which is the current industry practice in the USA. Following the example of the Iceland Deep Drilling Project (IDDP) this estimate for the SSGF is much too conservative if production from depths of 4 to 5 km were to be developed.

Table 1. Some metal concentrations (mg/kg) in the brine produced from well State 2-14, in the SSGF, calculated to reservoir conditions at >300°C (data from the Salton Sea Scientific Drilling Project, Elders and Sass, 1988)

Li	Rb	Cs	Mn	Fe	Zn	Cu	Pb	Cd	As
209	132	142	1500	1710	507	6.8	102	2.3	5

Although the SSGF brines contain unusually high concentrations of metals (Table 1), previous attempts 15 years ago by the principal operator of the SSGF (CalEnergy), using solid-liquid ion exchange to extract zinc from ZnCl, proved to be uneconomic at that time. as battery grade lithium carbonate is currently selling at about 16,000 USD/tonne, the concentration of lithium in the SSGF, ranging up to 250 mg/kg is particularly valuable. The value of lithium in solution at drillable depths in the SSGF exceeds tens of billions USD. The geothermal plants *currently* operating at the SSGF have the potential to extract an impressive 2.5 billion USD/year of lithium. If the entire known Salton Sea geothermal resource area were to come into production, these quantities scale to 14.4 billion USD/year. There are hundreds of geothermal plants around the world currently generating a total of 30 times as much power as the SSGF, suggesting an enormous potential impact if combined hydrogen production and metal extraction were to be developed globally.

5.3 Combination and Integration

The overarching principle of such a comprehensive scheme is the synergism of integrating different technologies that use supercritical fluids to improve the economics of geothermal resources. Figure 3 presents one configuration of how this integration could occur for a scenario where the supercritical or superhot geothermal fluid is not suitable for direct introduction in a turbine and so heat exchangers are used to heat a clean water as the working fluid. Many other combinations are possible, depending on the specific local conditions.

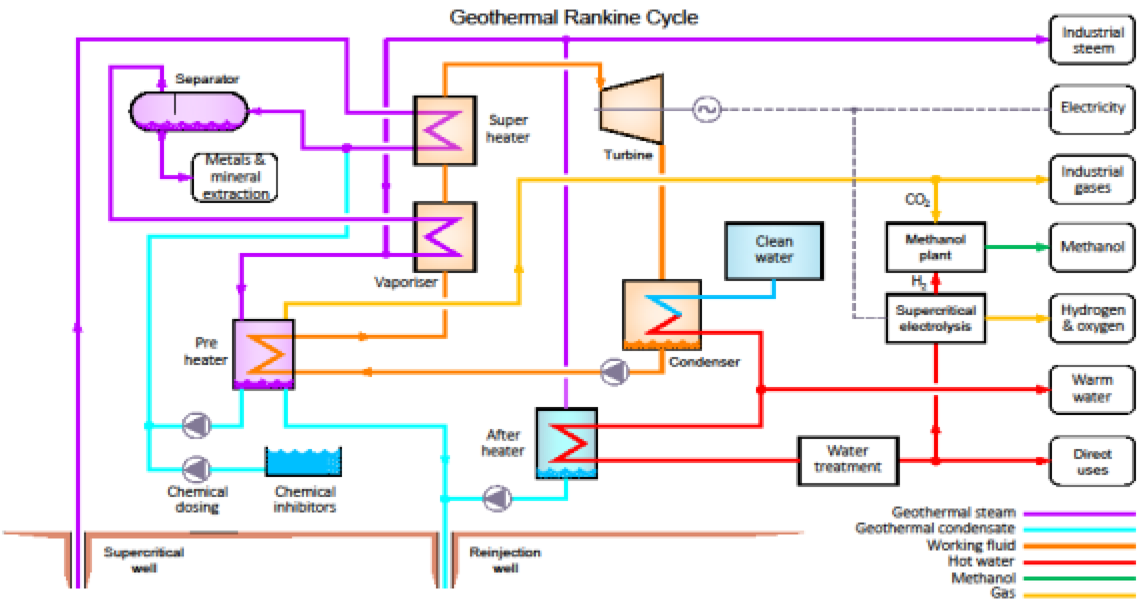

Figure 3. A possible comprehensive scheme for using supercritical or superheated fluids with integrated and flexible production of industrial steam, electricity, industrial gases, methanol, hydrogen and hot water and desalinated water for direct uses. This configuration uses clean water, heated by supercritical or superhot fluids, as the working fluid in a turbine.

6. USING GEOTHERMAL RESOURCES TO REDUCE GHG EMISSIONS: THE EXAMPLE OF CALIFORNIA

Reducing GHG emissions from electricity generation is clearly desirable but, in the case of California, the most populous state in the USA, electricity generation contributes only 16 % of the GHG emissions. In California by far the largest source of GHG emissions is transportation which contributes 41% of total emissions (California Energy Commission, 2017). Therefore, the biggest potential for reducing GHG emissions in California, and globally, would come from using hydrogen for transportation. Increased use of electric vehicles will play an important role in reducing GHG emissions particularly in urban environments. However, hydrogen powered vehicles, have a greater range and flexibility, particularly for larger engines used in ships, trains, trucks, and buses.

Schemes like that illustrated in Figure 3 have the potential to reduce CHG emissions from many different sources. For example, in industry using geothermal sources for process heat and using electrolytic hydrogen instead of producing it from reforming natural gas. In Iceland ~90% of buildings use geothermal hot water for space heating. In California, while there is a lesser need for space heating, air conditioning is a large energy consumer. The Imperial Valley of southern California has a climate with more than 100 days in the year when the temperature exceeds 100°F (38°C). This area produces almost 900 MWe of geothermal electric power. Downstream of these plants, the hot water from both flashed steam and binary plants is injected into disposal wells, without using any of its useful heat. This wasted energy could be applied for district heating and cooling for domestic and industrial users, and by agricultural users such as sugar refining and meat packing plants in the Imperial Valley, that currently rely on natural gas. Geothermal district heating schemes are common in colder climates like Iceland but operating "district cooling" schemes are virtually unknown, although there are some individual buildings that use geothermal water for both heating and cooling.

Elders et al. (2018 & 2019) have put forward a plan to begin implementation of the concept at the SSGF in California. As a first step, they proposed constructing and operating a testbed, a Geothermal Demonstration Facility, that would bring together several innovative and synergistic systems, including state of the art electrolysis to produce hydrogen, osmosis (either forward or reverse) to produce deionized water for electrolysis, extraction of lithium chloride (or carbonate) (and other metals), and cascading the thermal effluent to produce hot and chilled water appropriate for district heating or cooling. Funding for this proposal is still being sought at this time. Meanwhile, two of the three operators at the SSGF have announced that they are beginning to develop experimental lithium extraction facilities.

7. DISCUSSION

7.1 Suitable Geothermal Fields Worldwide

Superhot fluids at less than supercritical pressures have been encountered in wells in numerous volcanic geothermal fields, Including the SSGF (Kaspereit et al., 2016) and elsewhere in California at the Geysers (Lutz et al., 2012). Deep wells drilled in Kakkonda in NE Japan (Muraoka et al., 1998), Larderello in Italy (Bertini et al., 1980), Los Humeros in Mexico (Gutiérrez-Negrín and Izquierdo-Montalvo, 2010), Menengai in Kenya (Mbai et al., 2015), and Puna, Hawaii, USA (Teplow et al., 2009) have all encountered temperatures above 374°C. By drilling deeper to reach higher pressures, development of supercritical geothermal resources could be possible there and in many other volcanic areas worldwide. For example, in Japan the Japanese Beyond Brittle Project (JBBP) is an ambitious EGS project to extract geothermal energy from >500°C neogranites (Muraoka et al., 2014). Another future possibility, when the technology and economics permit, is to produce useful energy directly from the worldwide submarine mid-ocean ridge systems (Elders, 2015). Vents discharging supercritical water on the sea floor have been directly observed at 5°S on the Mid-Atlantic Ridge (Koshchinsky et al., 2010). Similarly, if the technology can be developed, very high temperature energy could be extracted directly from magmas (Eichelberger et al., 2018).

7.2 Economic Implications

The economics of utilizing such supercritical and superhot geothermal fluids could be greatly enhanced by using a flexible and integrated approach. Using superhot water and electricity on site to make hydrogen fuel obviates the need to use electricity storage such as batteries or pumped storage at times when electricity demand is low, while keeping flow rates from the wells constant. Similarly, the higher enthalpy should improve the economics of extracting metals and minerals from the brines and making renewable methanol and desalinated water. Of course, not all these techniques will be applicable in any given case and a great deal of technological development will be necessary. This integrated approach will likely evolve in a stepwise fashion at different sites. We suggest that the Salton Sea Geothermal Field (SSGF) is the ideal site in the USA to begin.

8. CONCLUSIONS

We believe that the next big steps forward for the worldwide geothermal industry should be (1) development of supercritical and superhot systems, (2) development of advanced systems for electrolysis, and mineral extraction, etc., and (3) building and operating fully integrated power plants with hydrogen and metal production incorporated at the beginning rather than being "add-ons". Implementation of this plan will require cooperation of geothermal industry, electrical utilities, and consumers with participation at the outset by international, federal, state, and regulatory agencies, and with appropriate community involvement.

A major incentive for such cooperation is the goal of reducing GHG emissions. The reduction in GHG will come from keeping CO_2 out of the atmosphere by: (1) displacing hydrocarbon fuels used for the electricity generated, (2) making hydrogen for energy storage, (3) making hydrogen for transportation (4) creating a domestic supply of lithium for batteries used in Zero Emission Vehicles, (5) producing metals such as manganese and zinc, without smelting, and (6) replacing electricity and natural gas used for air-conditioning and space heating.

If comprehensive schemes like those illustrated in Figure 3 were to be implemented, the actual size of the reduction in GHG emissions is hard to quantify. It would depend on the degree of adoption by the geothermal industry, but it would be large and furthermore replicable at geothermal plants worldwide. We envision ultimately that, depending on local conditions, fully integrated geothermal plants will become factories producing hydrogen, metals, and water for heating and cooling, while producing electricity, with much of it consumed internally. Our ambitious long-term goal is to have the geothermal industry recognize and adopt the concept that reducing GHG emissions, is not only necessary in view of Climate Change, but should also be profitable. The transition will be difficult, but we must begin.

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